Sunpower, Inc.

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Introduction

The subject of this SMB project is a system that burns biomass fuels and converts the resulting heat to electric power by means of a free-piston Stirling engine. The first systems to be commercialized through this project are designed to burn wood fuels, because at present those fuels are widely used by a large, initial target market: homeowners who burn wood for heat. Later products will be designed to burn other types of biomass fuels as they become commercially available.

The overall objective of this SMB project is to develop SMB systenms that are fuel-flexible, efficient, simple to operate, whose operation has minimum negative impacts on the environment, and which that provide power in the range of electrical generation sizes smaller than 20 kW for domestic and international markets. The Phase 1 objective was a feasibility study that includes a market assessment, resource assessment, preliminary system design, assessment of relevant environmental and safety considerations, evaluation of financial and cost issues, and preliminary business plan and commercialization strategy.

This project achieved all Phase 1 objectives with respect to the first product in a line of SMB systems. That product is a system that cogenerates as much as 1 kW of electrical power together with heat for water and space heating in single-family dwellings. Later products will have electrical output capacities as high as 20 kW for larger residential, commercial, and agricultural applications.

Potential Markets

The market

The target market for these products is in individual residential, small commercial, and farm buildings worldwide wherever low-cost biomass fuel is abundantly available and electric power is unavailable, unreliable, or expensive. These products will be sold in three market segments: remote homes in developed countries, off-grid rural electrification in developing countries, and on-grid distributed power production worldwide.

Near-term sales opportunities for these products are in the forested territories of the higher latitudes where wood is burned extensively as a fuel. The aggregate sizes for all single-family residences in North America, Europe, and developing countries are estimated to be $200 billion, $230 billion, and $150 billion, respectively.

The biomass fuels

The initial models of these residential cogeneration products will burn wood pellets and fuel wood. Most wood pellets used for residential heating are made from sawdust and ground wood chips, which are waste materials from trees used to make furniture, lumber, and other products. Pellet fuels graded by The Pellet Fuels Institute must meet tests for density, dimensions, fines, chlorides, and alkali content. These physical and chemical properties are ideal for biomass combustion, but the processing that contributes these virtues also makes pellets the most expensive form of biomass fuel. Because they are densified, pellets can be profitably transported to distant markets.

Fuel wood is harvested as a fuel source rather than as lumber or for other purposes. Production is highest in the forested territories of the northern and central latitudes. The United States produces the most fuel wood in North America. Russia produces the most fuel wood in Europe, but per capita fuel wood production is much greater in the Scandinavian and Baltic countries, especially in Finland.

Competing demand for these biomass fuels

The primary competing demand for these biomass fuels is residential heating. The new residential biomass cogeneration products will not change this usage for the initial target market of homeowners who already burn wood for heat. Later the market will be expanded to displace expensive and polluting residential electric and fossil fuel heat sources, which will increase the demand for biomass fuels.

The optimum size for this technology

Historically, Stirling engines have been fabricated in capacities from 1 W to more than 1 MW. The optimum size for this technology is an economic issue relative to competing technologies for the same application, and it has not yet been determined in the marketplace. Stirling engines work by sensible heat transfer into and out of the engines, so they are believed to be most competitive as their size is reduced and their surface-to-volume ratio increases. Therefore, free-piston Stirling engines are generally believed to be most economically competitive with other technologies at power levels less than 20 kW; this advantage is believed to increase as size is further reduced. This favors an economy of scale based on high-volume manufacturing rather than on high unit capacity.

The demand for this type of power

Such a low power range has a major economic advantage over larger biopower technologies that compete with other large generating technologies in a wholesale deregulated electric power market. Residential biomass cogeneration systems can compete on the retail market where competing prices are highest. This creates opportunities for higher margins and smaller financial risks. Furthermore, avoidance of a separate heating bill also creates a large economic incentive for homeowners to convert from expensive electric heat to biomass cogeneration.

For example, for the 1 million off-grid homes in North America, the competing prices of electricity range as high as $0.75/kWh or more and the primary heat source for many of these homes is wood. In North America, 15 million homes burn wood for heat, including 5 million in the Northeastern states (where homeowners pay the highest electric utility rates in North America). In addition, 9 million homes are heated by electricity.

Of the countries with the highest average household electric utility rates, all but Korea and Japan are in Europe. In Europe, too, many are heated by wood, including 1.3 million in Scandinavia, 600,000 in Austria, and 2.5 million in France. Many more homes, including 2.5 million in Scandinavia, 300,000 in Austria, and 9 million in France, are heated by electricity.

Fit of the optimum size to the demand
In middle-class, single-family residences in developed countries, the average annual electrical load for purposes other than space heating and cooling is 1 kW. The average daily peak electrical load is ~1.5 kW and momentary surge loads can be as great as 6 kW as motors in home appliances start up. The peak load exceeds 1 kW for only a few hours per day, however, and surge loads occur for only a few minutes per day.

Sunpower believes that the greatest home economy will be achieved by residential cogeneration systems that serve the average annual electrical load and use other sources of electrical power, such as an electrical utility grid or a battery bank and an inverter, to serve peak and surge loads. Thus, the optimum size of free-piston Stirling engines fits especially well with the average annual electrical demand of the single-family residential market.

Biomass requirement and availability
A 1 kW residential biomass cogeneration system for markets in northern latitudes may be designed to burn the least fuel required for the system's electric generating capacity, or to burn more wood to serve the full residential space heating requirement. For the 1 kW electrical generating capacity, a residential biomass cogeneration system will burn ~1.5 kg of wood pellets per hour. This projects to ~6.5 tons of wood pellets per year. (The corresponding amount of fuel wood depends on the moisture content of the fuel.) This amount is similar to the amount burned by homes in Sweden that use pellet furnaces as their primary heat sources

Wood pellets are widely available for retail sale in North America and northern Europe. They are delivered directly to homes throughout Sweden south of the 60th parallel, where more than 80% of the population lives. Self-cut fuel wood is commonly cut on the homeowner's own woodlot. Purchased fuel wood is delivered by the retail vendor, usually an individual entrepreneur.

Projected system capital cost
Because SMB systems can be targeted at high margin markets where the competing COE is highest, entry prices for these systems can be unusually high. The cost of a competing residential solar photovoltaic electric generator system capable of providing the same 24 kWh/day every day of the year in northern forested territories (where insolation is low) ranges from $50,000 to $100,000. An international distributor of renewable energy systems believes that the North American remote home market will pay $10,000 for 1-kW residential biomass cogeneration systems, i.e., $10,000/kW.

To open larger markets, prices will need to be reduced, but Sunpower believes this will be achievable as manufacturing volume increases. For sale to on-grid markets, prices may be reduced to $3,500/kW or lower. The target high volume system manufacturing cost is $1,000/kW.

The cost of electricity for the proposed market
The economics of the cogeneration of electricity and heat differs fundamentally from those of electric generation, whichis critical in enabling residential biomass cogeneration products to compete aggressively against all electric generating technologies. In both electric generation and cogeneration, the COE increases with the system capital cost, the cost of fuel, and the O&M costs. In cogeneration, however, this cost is reduced by the market value of the heat that is cogenerated and that does not have to be purchased separately from another heat source. Furthermore, the effective cost of cogenerated electricity decreases as the avoided market value of the heat increases. Therefore, the very same cogeneration system produces electricity at different prices, depending on the values of the avoided cost of heat.

Thus, even at entry market prices for equipment, when it displaces heat from a wood stove, a 1-kW residential biomass cogeneration system in a home in a northern latitude cuts the COE in half. When the competing heat source is a more expensive oil furnace, the reduction in the effective cost of cogenerated electricity is greater, and when the competing heat source is electricity, the reduction is so great that the effective cost of cogenerated electricity actually becomes negative! Furthermore, it becomes most negative where competing electric rates are highest. In France, for example, where the household electric utility rate is $0.17/kWh, a 1 kW residential biomass cogeneration system sold for $9,500 would cogenerate electricity at -$0.10/kWh when it displaces heat from an electric heating system. Only through cogeneration can the effective COE be negative.

System Design

As shown in Figure 8, in the residential biomass cogeneration systems being developed, fuel is first pyrolyzed at ~55°C and then mixed with recuperatively preheated secondary air for combustion at ~1400°C. The resulting exhaust gas is channeled over the head of the free-piston Stirling engine as required by the electrical load, or diverted past the engine to the recuperator. Approximately three-quarters of the heat absorbed by the engine at 550°C is rejected into the engine's coolant fluid, which is circulated to the thermal load by an inertia water pump driven by the vibration of the engine body. The rest of the energy absorbed by the engine appears as electric power generated by the linear alternater mechanically linked to the engine's piston.

The combustion exhaust gas leaves the engine at ~700°C; additional sensible heat is then recuperated into the combustion air to reduce the amount of biomass fuel required to maintain the engine's head temperature. An optional condensing heat exchanger may be employed to recover the latent heat in the exhaust.

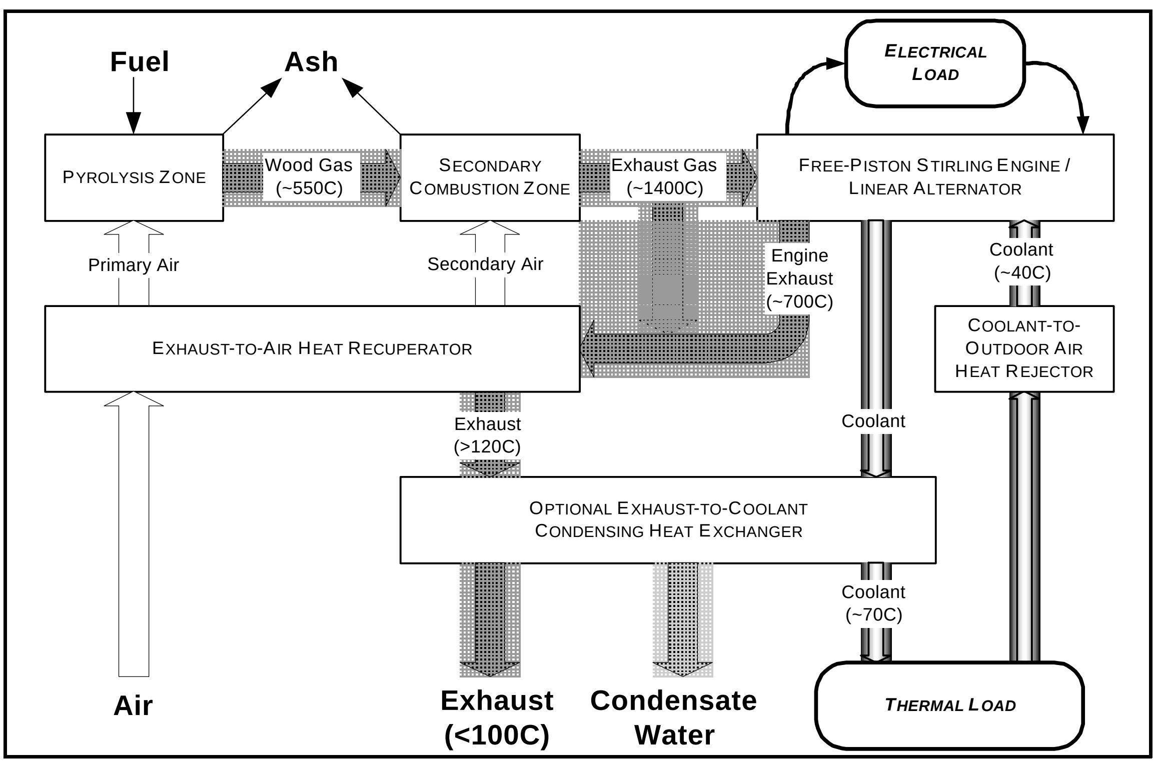

Figure 8.

The thermal load is composed of parallel loops for domestic hot water, space heating, and system heat rejection. When hot water and space heating loads do not demand all the heat cogenerated with the electrical power, that excess heat must be rejected from the system to the environment.

Several such proof-of-concept prototype systems have been fabricated and their electrical and thermal performances have been confirmed. Further testing is required to determine whether the design requires improvements to reduce cost, increase reliability, and verify compliance with safety and environmental regulations.

System specifications

On the basis of experience with similar biomass burners and engines, as well as proof-of-concept prototype residential biomass cogeneration systems, the following specifications for the first residential biomass cogeneration system products are forecast:

Size	
Dimensions	102.0 cm H x 76.2 cm W x 56.0 cm D
Electrical Output Power	1 kW
Thermal Output	3.8 kW (without supplementary combustion)
Efficiency	
Electrical	15%
Thermal	68%
Overall	83%
Reliability	
Engine Maintenance	None
Burner maintenance	Fueling and ash removal
Mean Time to Replacement	80,000 h
Environmental emissions	
Particulates	<1g/h
CO	<10 ppm
NOx	<100 ppm
SO_2	nondetectable
Total VOC	<20 mg/m^3)
PAH	100 mg/h

Current use of this technology

The biomass combustion and free-piston Stirling engine technologies in the SMB systems under development are new technologies. Several biomass burners like the ones in proof-of-concept prototypes developed by Sunpower have been fabricated by the original developer and independently tested. Some are in use as residential furnaces and cookstoves. Several dozen free-piston Stirling engines have been fabricated by Sunpower and independently tested. Neither technology has been commercialized in manufactured products.

Technical issues resolved in Phase 1

During Phase 1, system issues concerning the interface of a residential biomass cogeneration unit to residential thermal and electrical loads were resolved. It was decided, for example, to configure domestic water and space heating thermal loads in parallel with the Stirling engine's heat rejection system. It was also decided to size the engine to serve the average annual electrical load rather than the peak and surge loads.

A preliminary estimate of manufacturing costs was also made to identify parts and assembly steps on which to focus additional manufacturing engineering to further reduce manufacturing cost.

Under separate internal funding concurrent with Phase 1, Sunpower also fabricated several proof-of-concept residential biomass cogeneration systems. These prototypes confirmed that small biomass combustion systems can be thermally linked to a free-piston Stirling engine, that the engine can respond to changing electrical loads over the full range of its electrical output capacity, and that the heat rejected by the engine can be transferred to a hot water circulation system.

Remaining technical issues

The major technical issues remaining to be resolved relate to manufacturing cost and quality and to the confirmation of expectations about performance and compliance with various safety and environmental regulations. With respect to manufacturing, repeatable, reliable, low-cost manufacturing processes remain to be developed in the factory in which they are to be performed. The performance and compliance of units coming off the factory's production line remain to be confirmed through laboratory tests and field trials.

Environmental effects of using or harvesting biomass

Of course, the harvesting of biomass may or may not be conducted in a sustainable manner, and local populations will need to discipline themselves to do so. The raw materials for pellet fuel production would often otherwise make their way into the municipal solid waste system; however, the widespread commercialization of residential biomass cogeneration systems may have a beneficial impact on municipal solid waste streams. Furthermore, if large numbers of homeowners use these products to convert their homes from fossil fuel or electric heating systems, these systems will have beneficial impacts on global warming and acid rain.

Air emissions

On the basis of independent measurements of air emissions from a similar two-stage biomass burner fabricated by the original developer, extremely clean emissions performance satisfying the strictest local regulations is expected. The forecast particulate emissions specified are as low as the best pellet and catalytic wood stoves, and the CO emissions are only 25% of the gas industry standard for CO-free combustion.

By-Products

The most economically significant by-product of electrical generation in the SMB systems under development is heat. This cogeneration of heat enables these systems to compete aggressively with other sources of electrical power. In most localities, the ash produced by the planned residential biomass cogeneration systems will be a beneficial soil amendment in homeowners' gardens. One exception is a region in northern Sweden that was contaminated by the Chernoble nuclear accident. The ash from wood harvested in this region is classified as nuclear waste by Swedish authorities, who forbid its disposal by return to the forest.

Future Development

Partnerships

In 1994, Sunpower licensed its free-piston Stirling engine technology to Wood-Mizer Products, Inc. Wood-Mizer manufactures portable sawmills and distributes them in 104 countries worldwide. In 1996, Wood-Mizer assigned its free-piston Stirling engine rights to External Power, LLC, a new firm created by Wood-Mizer to focus on the commercialization of these engines. External Power plans to manufacture free-piston Stirling engines in various kinds of products. External Power plans to distribute residential biomass cogeneration systems through Wood-Mizer's worldwide network and through other distribution channels.

External Power has also formed a strategic partnership with Energidalen, a biomass energy research center and business incubator in Solleftea, Sweden. Energidalen will perform market analyses for External Power's products in Europe, develop distribution channels, and recruit European investors. Energidalen will also test External Power products to facilitate their approval for sale in the European Union. In addition, Energidalen will make joint proposals with External Power to the European Commission for financial assistance to promote the commercialization of these products throughout the European Union.

To bring residential biomass cogeneration systems to market widely, External Power plans to recruit strategic corporate partners in various industries involved in the biomass energy chain, including forestry, pellet fuels, electric power, residential heating, and white goods.

External Power also plans to recruit other strategic corporate partners and to sell engines to them as original equipment manufacturers for other commercial applications of free-piston Stirling engines. One such application is expected to be natural gas- and propane-fueled residential cogeneration systems.

Sources of financing for future development and deployment

External Power plans to finance the development of its first residential biomass cogeneration products and the first factory to produce them by means of a 50% cost-shared Phase 2 project in the DOE Small Modular Biopower Program. Half the cost of this project will be guaranteed by Wood-Mizer Products, Inc. Subsequently, External Power will seek to finance widespread field trials of these products in North America and Europe by means of a Phase 3 project in the same program, with cost equally shared by External Power, DOE, and the European Commission. Financing for the startup and expansion of full-scale production, distribution, sales, and service will be sought from banks, strategic corporate partners, venture capitalists, and private and public offerings of stock, as well as from retained earnings on early sales in high margin markets.

Marketing and original equipment strategy

External Power is still developing its marketing and distribution strategy, but expects to distribute residential biomass cogeneration systems to homeowners through various distribution channels, including Wood-Mizer's worldwide distribution network, pellet fuel distributors, heating equipment distributors, and electric utilities as well as through direct sales via electronic commerce. Where appropriate, External Power also plans to sell free-piston Stirling engines to original equipment manufacturers for inclusion in cogeneration and electrical generation systems sold under their labels and brand names.

Market entry and growth strategy

Directly and through strategic partners, External Power plans to offer residential biomass cogeneration products first to the off-grid market in the forested territories of northern North America where the competing COE is very high. In this region homes have a substantial thermal load and homeowners are accustomed to burning wood for heat. External Power then plans to expand sales to northern Europe where similar conditions prevail, except that few homes are off-grid but the competing COE from electric utilities is much higher than in North America. Only later will External Power attempt to enter on-grid markets in North America, probably first in the Northeastern States and in high-cost rural load pockets of electric utilities elsewhere.

External Power products will be marketed first to homeowners who are already accustomed to burning wood for heat, and later to homeowners who wish to glean the large economic and environmental benefits of converting their homes from oil and electric to biomass heat sources.

In parallel, External Power will distribute residential biomass cogeneration systems in developing countries through Wood-Mizer's worldwide network of distributors. Through other strategic partners, External Power will expand operations in these countries as their markets mature.

As other biomass fuels become commercially available for residential use, External Power will develop new products to burn those fuels. Possible future commercial biofuels include herbaceous crops and wastes, biodiesel oil, and ethanol.

Finally, External Power also plans to develop products with electrical capacities as high as 20 kW or more for larger residential, small commercial, and agricultural markets.